

# **AVIRIS In-Flight Calibration Experiment, Sensitivity Analysis, and Intraflight Stability**

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## **1.0 INTRODUCTION**

Validation of the calibration of Earth-looking sensors in the operational environment is essential to allow quantitative scientific research and applications from the measured data. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an Earth-looking sensor (Green et al., 1998a) that measures solar reflected spectra from 400 to 2500 nm at nominally 10-nm sampling. These spectra are measured as images from either the high-altitude platform or low-altitude airborne platform. From the high-altitude Earth Resources 2 (ER-2) aircraft, the images have a nominal swath of 11 km and length of up to 800 km, with 20- × 20-m spatial resolution. From the Twin Otter, low-altitude aircraft, the images have a nominal swath of 2 km and length of up to 200 km with 4- × 4-m spatial resolution.

Calibration is essential for AVIRIS to meet the requirements of the Earth science research and applications community. A multilevel calibration strategy is implemented with AVIRIS. The primary spectral, radiometric, and spatial calibrations of AVIRIS occur in the laboratory before and after each flight season (Chrien et al., 1990, 1995, 1996, 2000). During the flight season, additional radiometric calibration checks are performed about once per month, when AVIRIS is in the hangar. For detailed calibration monitoring, the onboard calibrator is viewed by the AVIRIS instrument before and after each data flight line is acquired. However, it is the in-flight calibration experiment that provides an end-to-end test of AVIRIS calibration while AVIRIS is acquiring data in the flight environment. For an in-flight calibration experiment, AVIRIS acquires airborne data over a calibration target designated on a dry lake bed surface. At the same time as the AVIRIS data are measured, in situ measurements are acquired that describe the atmosphere and surface properties at the calibration target. These in situ measurements are used to constrain a radiative transfer code and independently predict the radiance at the AVIRIS sensor. This prediction is then compared to the radiance measured by AVIRIS for the calibration target on the dry lake bed surface. In each year since 1987, in-flight calibration experiments have been performed, to assess the calibration of AVIRIS in the flight environment. The results of these in-flight calibration experiments have been reported (Green et al., 1988; Conel et al., 1988; Green et al., 1990, 1991, 1992, 1993, 1995, 1996, 1998b, 1999). This paper presents the results of the in-flight calibration experiment performed on the 24<sup>th</sup> of September 1999, at Rogers Dry Lake, California. In addition to the in-flight calibration experiment, a sensitivity analysis of the predicted radiance to the accuracy of the in situ measurement is presented for this in-flight calibration experiment. Finally, analyses are performed to show the intraflight stability of AVIRIS for five consecutive overflights of the calibration target.

## **2.0 AVIRIS MEASUREMENTS**

Rogers Dry Lake is about a two-hour drive north of Los Angeles, near 35.0 degrees north latitude and 117.8 degrees west longitude. This site was selected for the dry lake bed surface and the proximity to the primary base for AVIRIS operations at the NASA Dryden Flight Research Center. On the 24<sup>th</sup> of September 1999, AVIRIS acquired data over Rogers Dry Lake during five consecutive overpasses. The overpass times were 17:40:28, 17:52:14, 18:04:41, 18:17:07, and 18:29:45 Universal Coordinated Time (UTC). Following the flight data acquisition, the data were entered into the AVIRIS data archive, calibration, and distribution subsystem at the Jet Propulsion Laboratory. These flight data were then requested from the archive for the in-flight calibration experiment analysis.

The surface calibration target was placed on the north end of Rogers Dry Lake. The target was 200 m long by 40 m wide and designated by large blue plastic tarpaulins placed at each end of the target, with

20-m buffer zones. The left portion of Figure 1 shows a full-scale AVIRIS image of Rogers Dry Lake acquired on the 24<sup>th</sup> of September 1999. The right-hand image of Figure 1 shows a zoomed enhancement. In this enhanced image, the calibration target demarcation tarpaulins are identifiable near the center. Uncalibrated AVIRIS data are reported as digitized number (DN) versus channel number. Figure 2 shows the uncalibrated AVIRIS data extracted for the calibration target area. The total signal, dark signal, and total minus dark signal are shown. These uncalibrated data were passed through the AVIRIS calibration algorithm where the radiometric and spectral calibration coefficients were applied. Figure 3 shows the calibrated AVIRIS spectrum for the first pass of the Rogers Dry Lake calibration target acquired on the 24<sup>th</sup> of September 1999. This spectrum has had both the laboratory and onboard calibrator derived calibration coefficients applied. This is the AVIRIS measured upwelling spectral radiance used for the in-flight calibration experiment analysis.

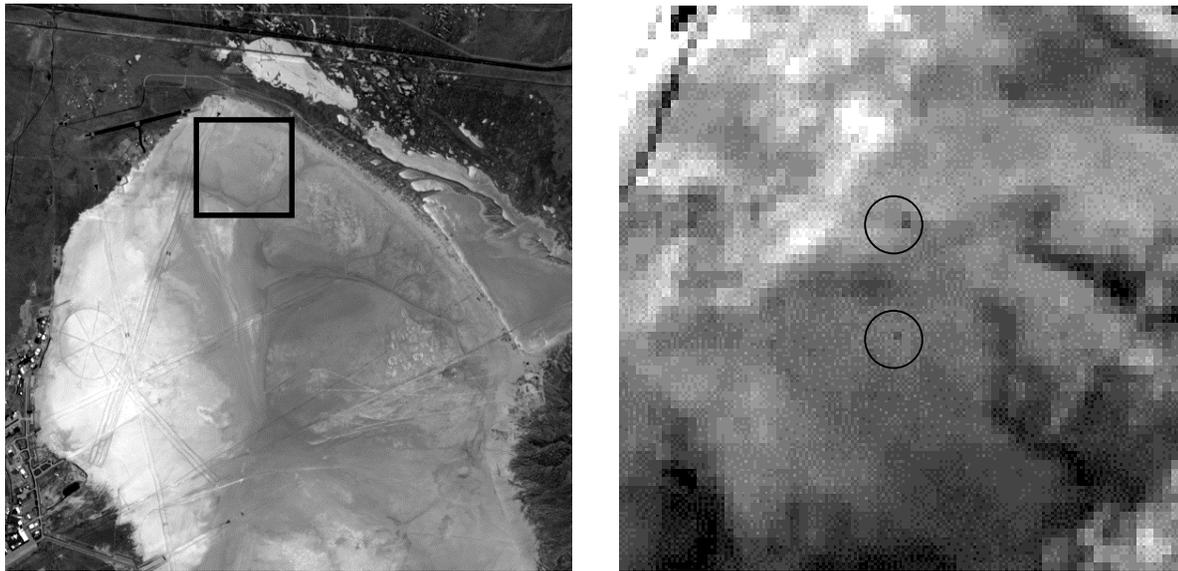


Figure 1. The left AVIRIS image is of Rogers Dry Lake, California, on the 24<sup>th</sup> of September 1999, with a box around the area of the calibration target. The right image is zoomed and enhanced to show the location of the calibration target with demarcation tarpaulins in the center of image. The demarcation tarpaulins are circled.

### 3.0 IN SITU MEASUREMENTS

In the same time frame as the AVIRIS overflight, in situ measurements are acquired for the surface and atmospheric properties of the calibration target located at 34.993 degrees north latitude and 117.834 degrees west longitude. These surface and atmospheric measurements are required to constrain a radiative transfer code to predict the total upwelling spectral radiance arriving at the AVIRIS instrument. The three critical in situ parameters are surface spectral reflectance, atmosphere optical depths, and atmosphere water vapor.

The surface reflectance data is acquired with a field spectrometer that measures the spectral region from 400 to 2500 nm at equal to or better than the AVIRIS spectral resolution. Surface reflectance measurements are acquired every few seconds as a set of transects is walked within the calibration target area. Periodically, measurements are acquired viewing a white reference of known spectral reflectance. During the time of the five AVIRIS overpasses of the calibration target on the 24<sup>th</sup> of September 1999, more than 1500 spectra were measured. From these measurements, the mean spectral reflectance of the calibration target is calculated. The reflectance calculation algorithm takes into account the known spectral reflectance of the reference standard as well as the bidirectional reflectance properties of the

reference standard. Figure 4 shows the reflectance spectrum calculated for Rogers Dry Lake calibration target on the 24<sup>th</sup> of September 1999. There is a gap near 1900 nm where the measured signal was near zero and deleted. Also shown is an estimate of the accuracy of the knowledge of the mean of this spectrum. With more than 1500 samples, the knowledge of the mean reflectance of the calibration target is excellent.

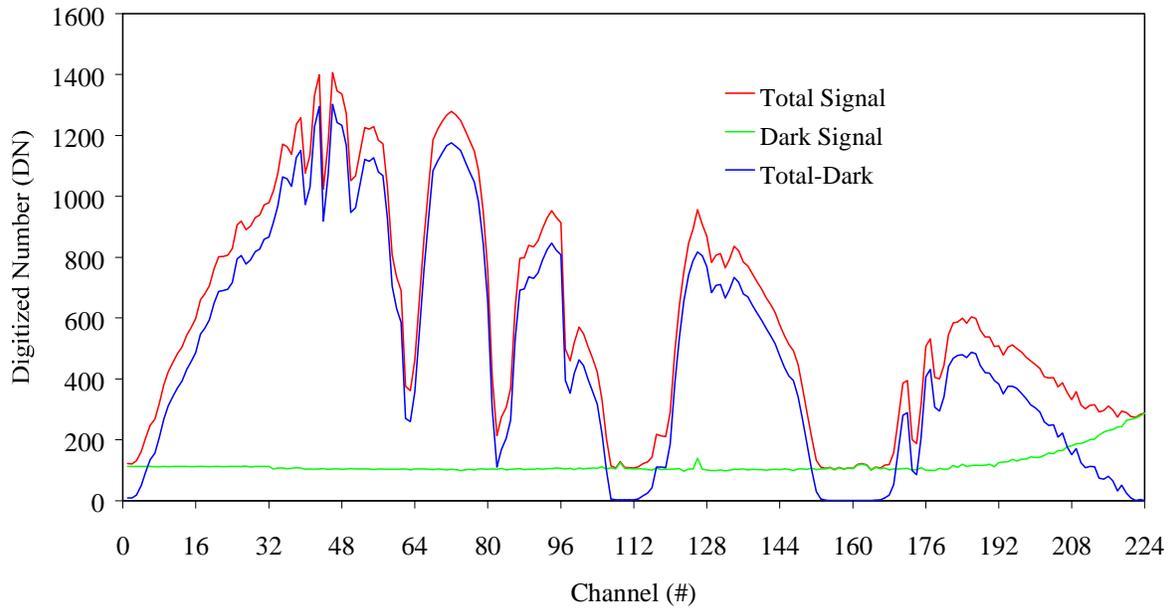


Figure 2. AVIRIS data extracted from the Rogers Dry Lake calibration target. The total signal, the dark signal, and the total minus dark signal are shown.

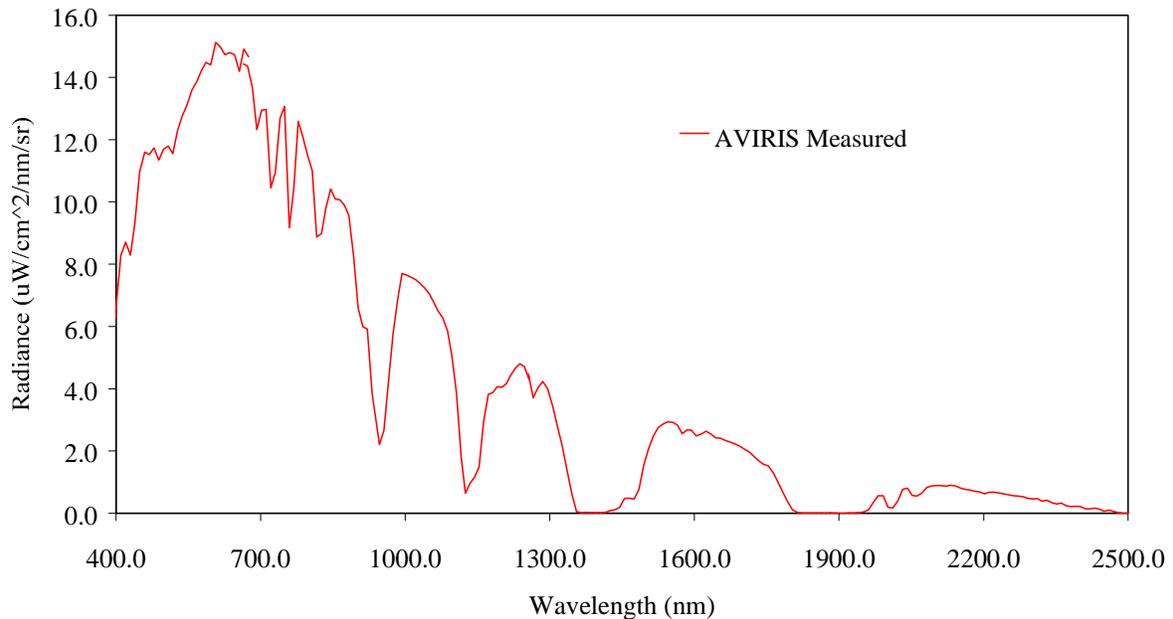


Figure 3. The AVIRIS measured radiance for the calibration target on Rogers Dry Lake for the 24<sup>th</sup> of September 1999.

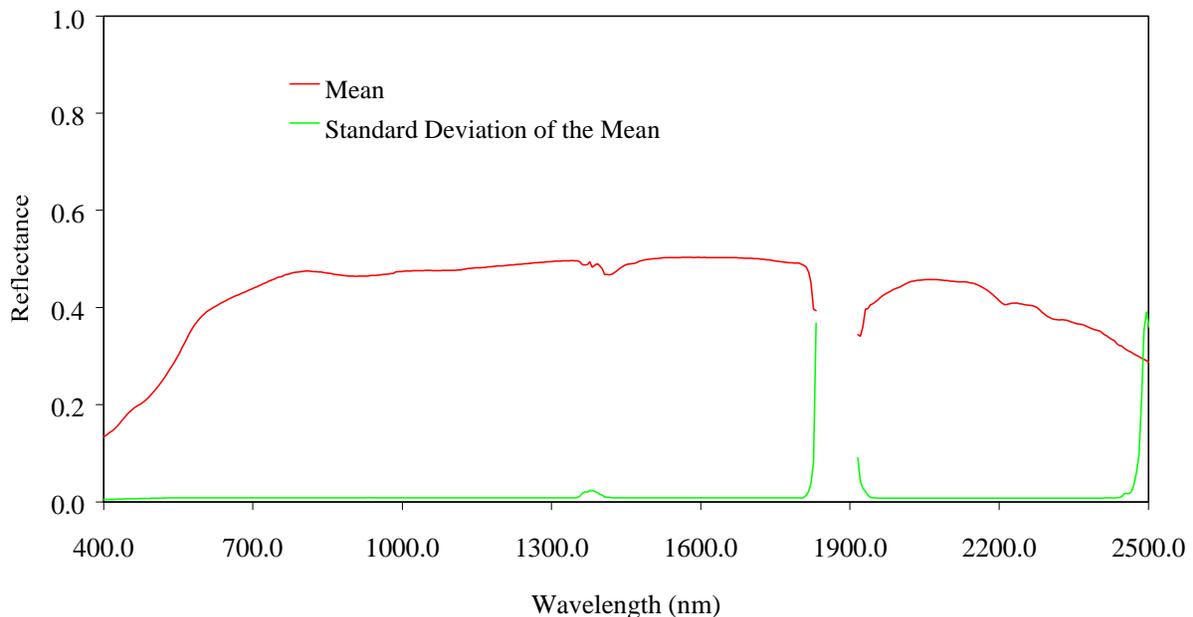


Figure 4. The in situ measured surface spectral reflectance of the calibration target on Rogers Dry Lake. This spectrum is the average, or mean, of more than 1500 measurements. The calculated standard deviation of the mean is shown as well.

Characterization of the scattering of the atmosphere is required for prediction of the radiance arriving at the AVIRIS instrument. Optical depth measurements are used to constrain the transmittance properties of the radiative transfer code to match the actual transmittance properties of the atmosphere at the time of the in-flight calibration experiment. Measurements for optical depth calculation are acquired with a solar radiometer. The solar radiometer used for this experiment measures the direct solar intensity in 10 discrete spectral bands positioned at 370, 400, 440, 520, 620, 670, 780, 870, 940, and 1030 nm. Measurements in these spectral bands are acquired every 30 seconds, from sunrise to local solar noon plus 2 hours while tracking the Sun. Figure 5 shows a plot of the natural log of the solar radiometer measurements versus the path length through the atmosphere. The optical depths calculated by the Langley method for each spectral band are given by the slope of the line. These optical depth values are nominal averages for the period of the AVIRIS in-flight calibration experiment. Figure 6 shows the measured optical depths as well as the modeled optical depths from the radiative transfer code. This best match was achieved for a 50-km visibility scaling of the radiative transfer code baseline 23-km rural aerosol model.

Atmospheric water vapor is calculated from the 940-nm measurement of the solar radiometer. This measurement is centered in an atmospheric water vapor absorption band. A modified Langley algorithm is used to calculate water vapor from the 940-nm data (Reagan et al., 1987; Bruegge et al., 1990). An instantaneous total column amount of 18.2 mm was calculated for the 24 September 1999 in-flight calibration experiment at Rogers Dry Lake, California.

For the day of the AVIRIS in-flight calibration experiment, a total ozone amount is obtained by the Total Ozone Mapping Spectrometer (TOMS) satellite sensor (McPeters, 2000). An amount of 285 dobson units was reported for the 24<sup>th</sup> of September 1999 in the Rogers Dry Lake region. A nominal carbon dioxide amount of 365 ppm was obtained for the period of autumn 1999 (Keeling and Whorf, 2000).

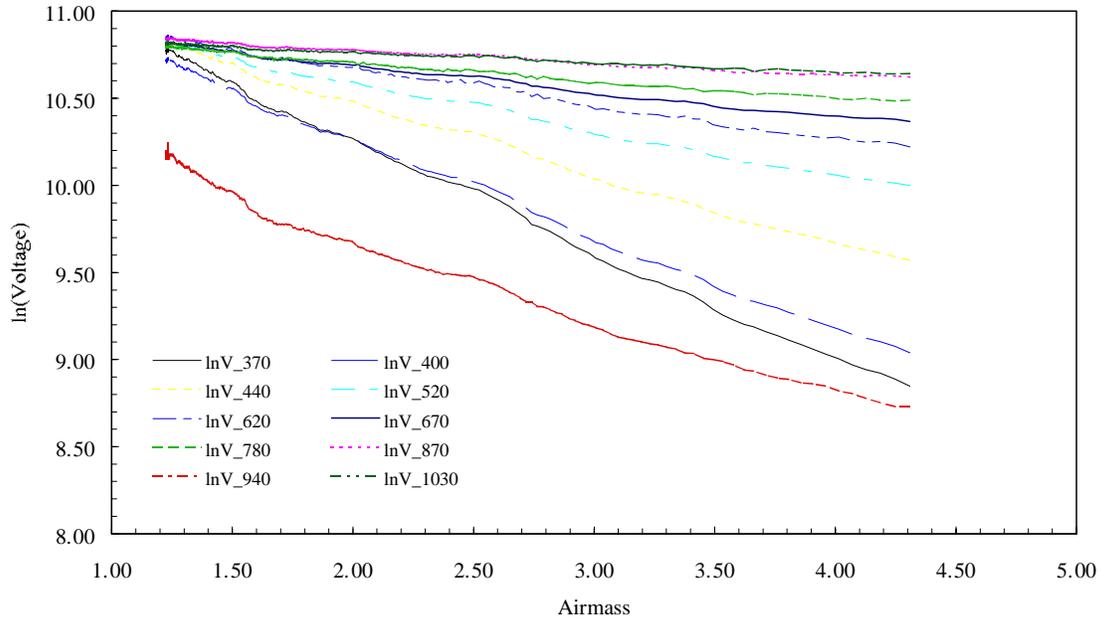


Figure 5. Langley plots for discrete wavelength solar radiometer measurements used to calculate the atmospheric optical depths for the AVIRIS in-flight calibration experiment on 24 September 1999.

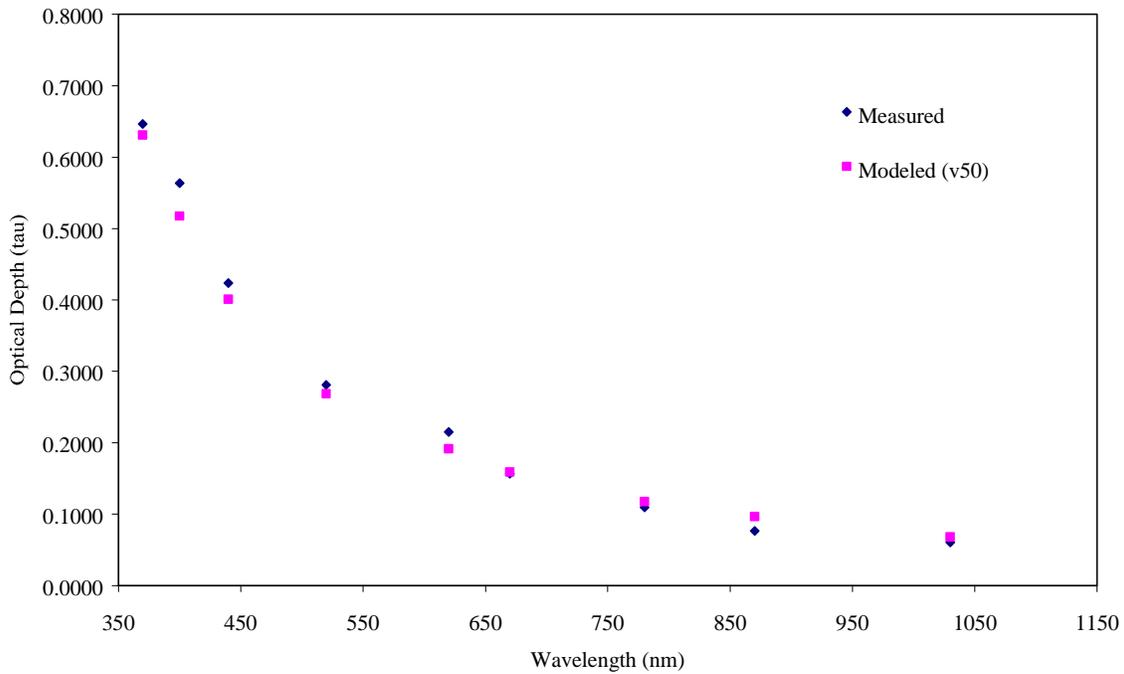


Figure 6. The measured and modeled optical depths for the nonwater vapor solar radiometer bands. The modeled optical depths are for the 23-km rural aerosol case rescaled to a visibility of 50 km.

#### 4.0 RADIATIVE TRANSFER MODEL PREDICTION

The in situ measurements and associated parameters are used to constrain the radiative transfer code and predict the radiance arriving at AVIRIS. The MODTRAN (MODerate TRANsmittance) software radiative transfer code (Berk et al., 1989) was used for this experiment. MODTRAN accepts a range of inputs that include surface reflectance, visibility, and aerosol model as well as water vapor. These

parameters are provided from the in situ measurements. The exact time and location of the calibration target are required as well. With these parameters, MODTRAN calculates the upwelling spectral radiance predicted to arrive at the AVIRIS instrument. Figure 7 shows the high spectral resolution predicted radiance calculated by MODTRAN for the 24<sup>th</sup> of September 1999 calibration experiment. Figure 8 shows the predicted radiance after convolution to the AVIRIS spectral calibration parameters.

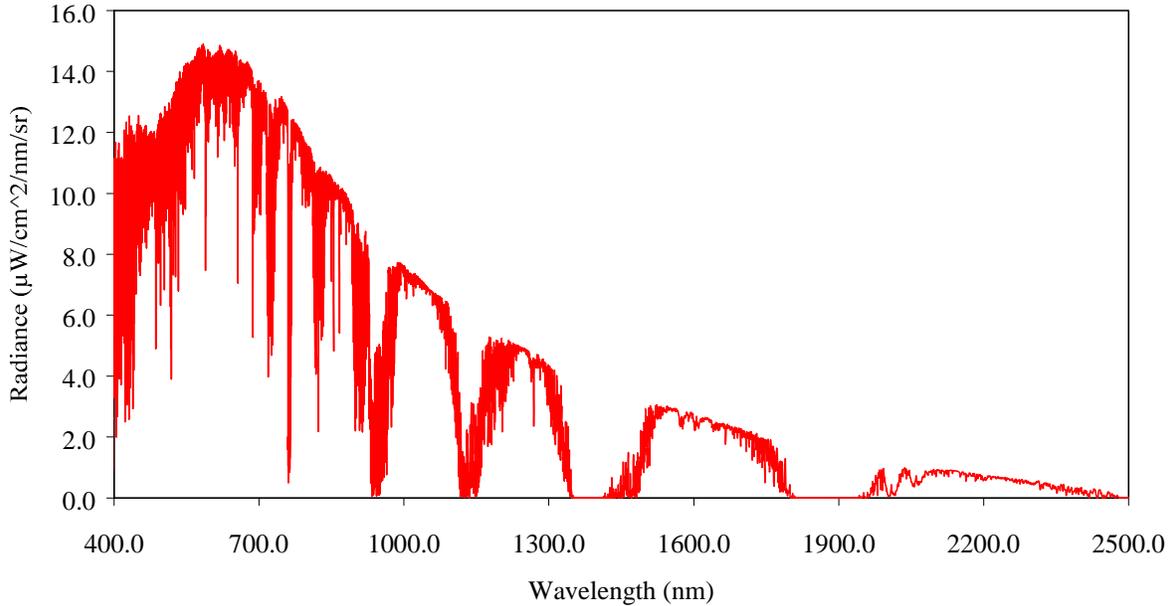


Figure 7. The high-resolution MODTRAN predicted radiance for the Rogers Dry Lake calibration target.

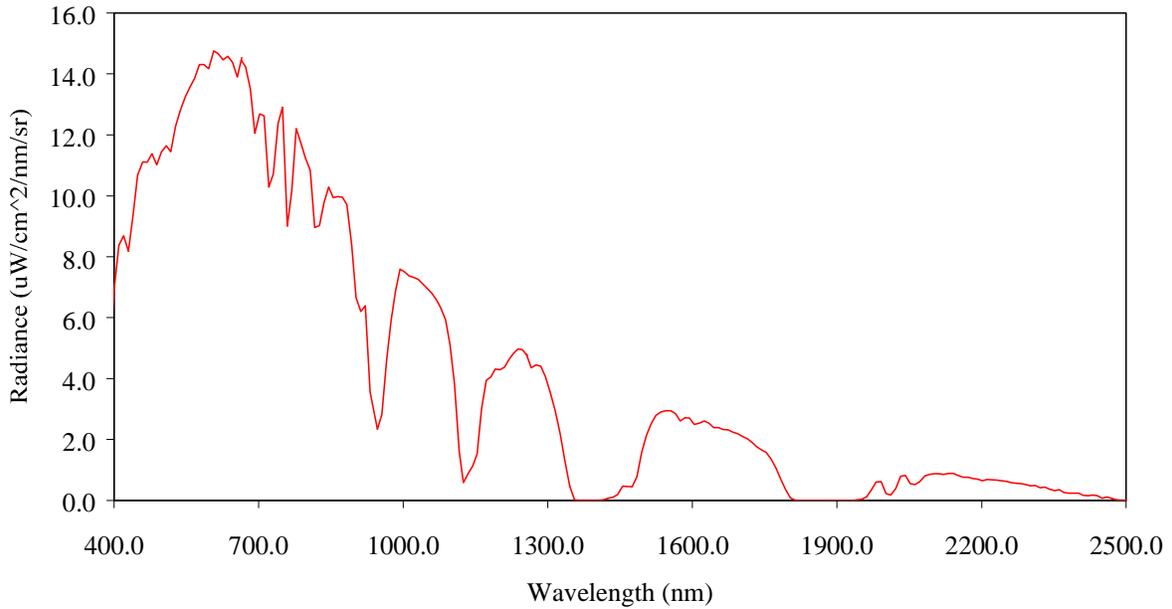


Figure 8. The MODTRAN predicted radiance convolved to the AVIRIS spectral calibration parameters for the Rogers Dry Lake calibration target on the 24<sup>th</sup> of September 1999.

## 5.0 IN-FLIGHT CALIBRATION RESULTS

The primary result of the in-flight calibration experiment is the comparison of the AVIRIS measured radiance with the MODTRAN predicted radiance for the calibration target. For the experiment held on the 24<sup>th</sup> of September 1999, the comparison is shown in Figure 9. The AVIRIS measured radiance spectrum is shown after spectral and radiometric calibration and use of the onboard calibrator. The MODTRAN predicted radiance is shown after constraint by the in situ surface, atmospheric measurements and regional atmospheric parameters as well as time and location of the calibration target. Comparison of the measured and predicted spectra shows good agreement across the AVIRIS spectral range. In percentage terms, the absolute average agreement across the spectrum is 96 percent, excluding the strong water vapor absorption regions. Figure 10 shows a ratio of the AVIRIS measured over the MODTRAN predicted radiance spectra. Portions of the spectrum with residual discrepancies occur near the water vapor bands at 940, 1150, 1400, and 1900 nm. Residual errors are also present near the oxygen band at 1280 nm and near the carbon dioxide bands at 2000 nm. Five potential residual error sources are the AVIRIS calibration, the AVIRIS calibration standards, the in situ measurements, the MODTRAN radiative transfer algorithm, and the underlying solar and atmospheric parameters in MODTRAN. These potential error sources are all topics of investigation.

In addition to the absolute radiometric calibration of AVIRIS, the radiometric precision of AVIRIS is of interest. In-flight radiometric precision is calculated from the signals measured from the AVIRIS onboard calibration during airborne data acquisition. The dark signal noise equivalent delta radiance (NE $\delta$ L) is calculated from the onboard calibrator dark signal and is reported in units of radiance. Figure 11 shows the dark signal NE $\delta$ L for AVIRIS on the 24<sup>th</sup> of September 1999. For comparison, the NE $\delta$ L calculated from the onboard calibrator in 1998 is shown as well. The lower the NE $\delta$ L, the more precise the measurement. These NE $\delta$ L spectra show the improvement from engineering modifications to the AVIRIS signal chain from 1998 to 1999. Another quantity of interest is the signal-to-noise ratio (SNR). Figure 12 shows the calculated SNR for 1999 in comparison to 1994 and 1987. This SNR is calculated from the NE $\delta$ L as well as the signal and photon noise expected from the AVIRIS reference radiance. The AVIRIS reference radiance is specified as the radiance from a 0.5 reflectance target illuminated at 23.5 degrees through the standard midlatitude summer model atmosphere.

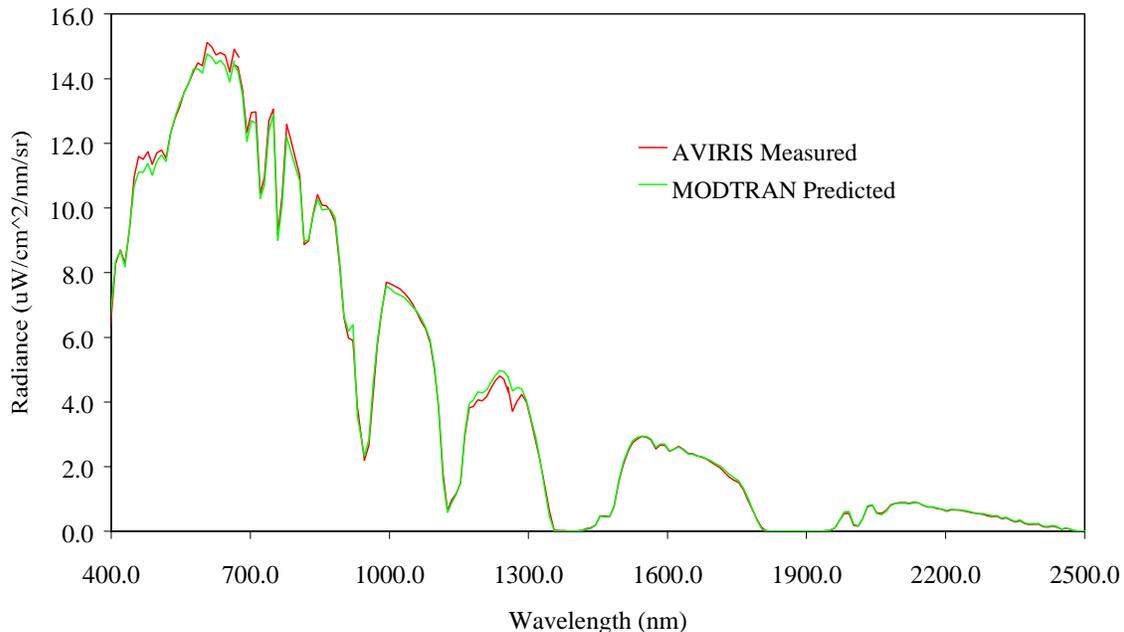


Figure 9. Comparison of the MODTRAN-predicted and AVIRIS-measured spectral radiance for the in-flight calibration experiment held on the 24<sup>th</sup> of September 1999.

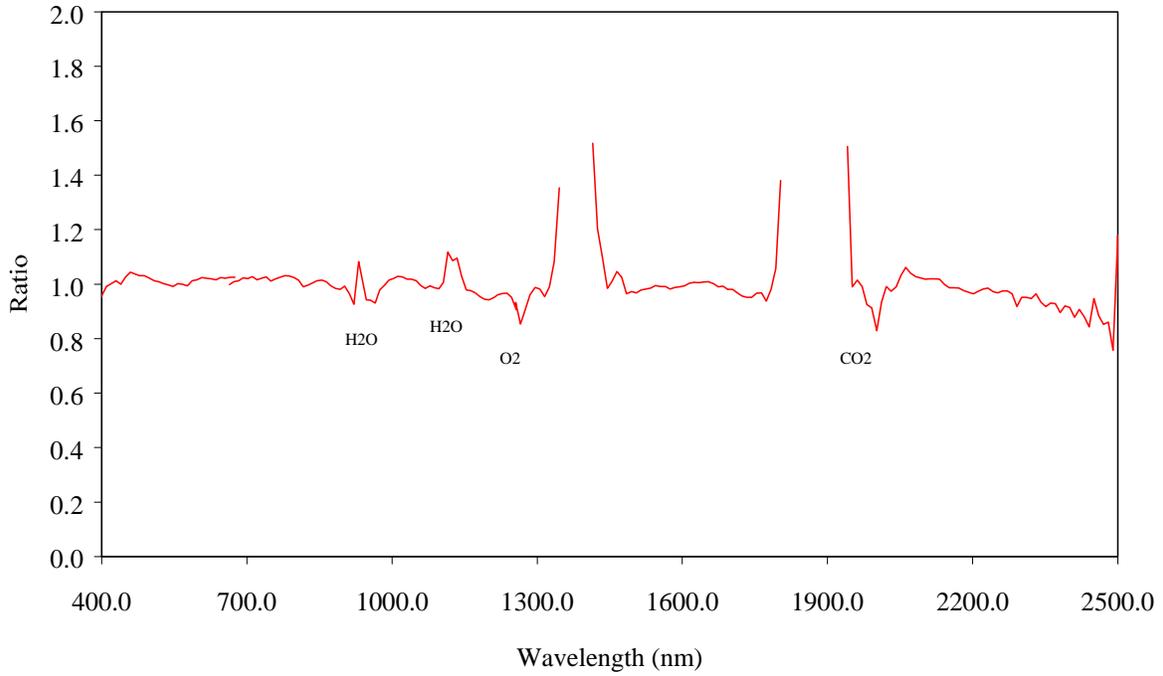


Figure 10. The ratio of the AVIRIS measured radiance over the MODTRAN predicted radiance of the calibration experiment. Distinct residuals occur near some atmospheric gas absorption features.

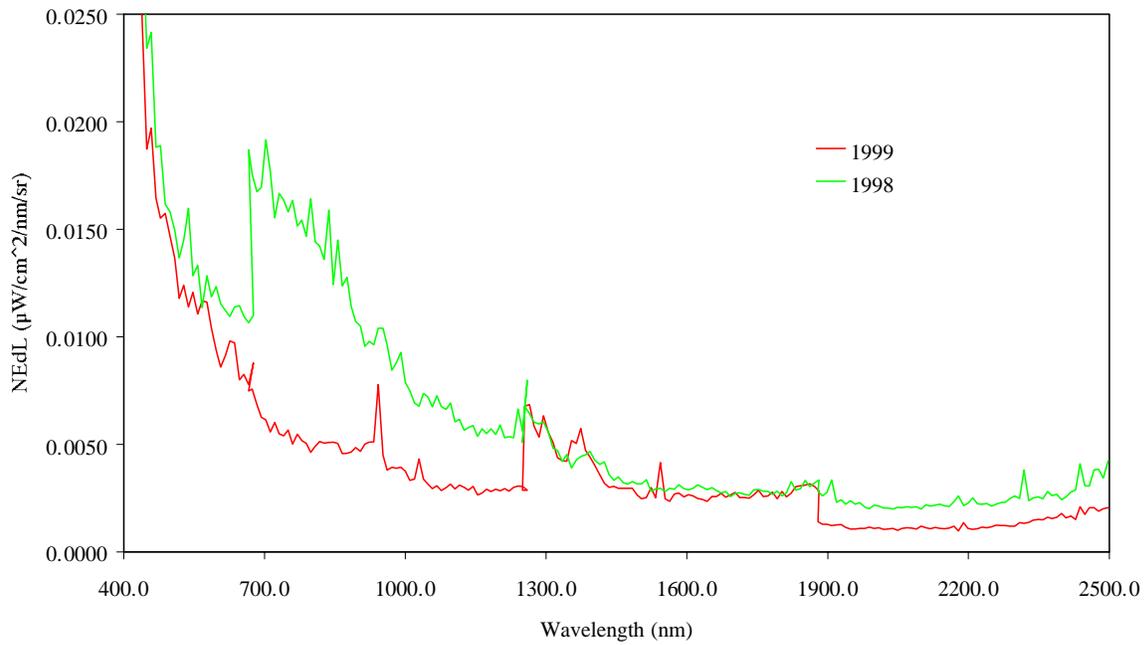


Figure 11. The noise equivalent delta radiance for AVIRIS in 1998 and 1999. A lower value implies better precision and a higher SNR.

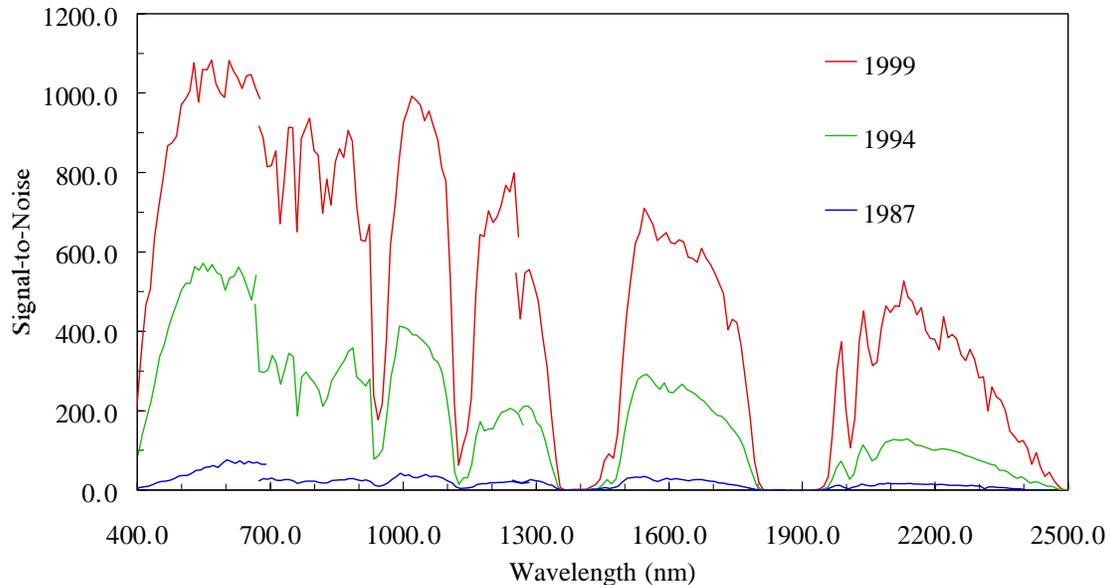


Figure 12. The calculated SNR for AVIRIS at the reference radiance signal level.

## 6.0 IN-FLIGHT CALIBRATION EXPERIMENT SENSITIVITY ANALYSIS

Every year, the AVIRIS in-flight calibration experiment is used to assess the calibration of the AVIRIS instrument in the flight environment. This experiment requires input of in situ measurements of surface reflectance, atmospheric water vapor, and atmospheric visibility to constrain the MODTRAN radiative transfer code. An analysis has been performed to assess the sensitivity to the accuracy of the in situ determined properties. The sensitivity is assessed by calculating the percent difference in radiance with and without an error in the given in situ measurement. The baseline case for this sensitivity analysis consists of the general time and location parameters as well as the specific surface reflectance, atmospheric water vapor, and atmospheric visibility determined for the in-flight calibration experiment on the 24<sup>th</sup> of September 1999.

The sensitivity of the predicted radiance to measured surface reflectance is investigated for an error of  $\pm 10$  percent in reflectance across the spectrum, from 400 to 2500 nm. Figure 13 shows the percent error in radiance as a function of error in the measured surface reflectance. The predicted radiance is strongly sensitive to the accuracy of the surface reflectance measurement. An error of 10 percent in reflectance translates almost directly to an error of 10 percent in predicted radiance. Many factors may effect the accuracy of the knowledge of the surface reflectance. Some of these factors are: homogeneity of the calibration target, thorough sampling of the calibration target, spectral and angular calibration of the reflectance standard, matching the AVIRIS measured calibration target with the in situ measured calibration target, clarity of the atmosphere, and timing of the ground measurements. It is important that all of these factors be accounted for to obtain accurate surface reflectance measurements of a calibration target.

Sensitivity to the in situ derived water vapor is examined for errors of  $\pm 10$  percent in the total column water vapor. Figure 14 shows the error in predicted radiance as a function of error in the water vapor measurements. The portions of the spectrum centered on the atmospheric water vapor absorptions are sensitive to the accuracy of the in situ determined water vapor. Errors in in situ derived water vapor cause spectrally localized errors in predicted radiance.

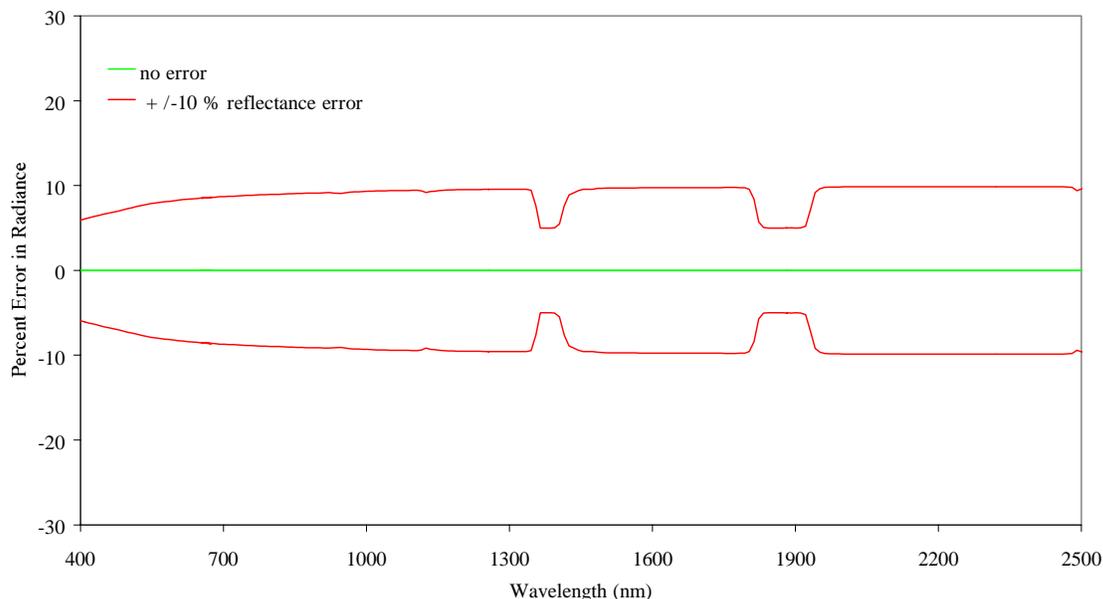


Figure 13. The error in MODTRAN predicted radiance as a function of the error in the measured surface reflectance. Results are shown for no error and  $\pm 10$  percent error.

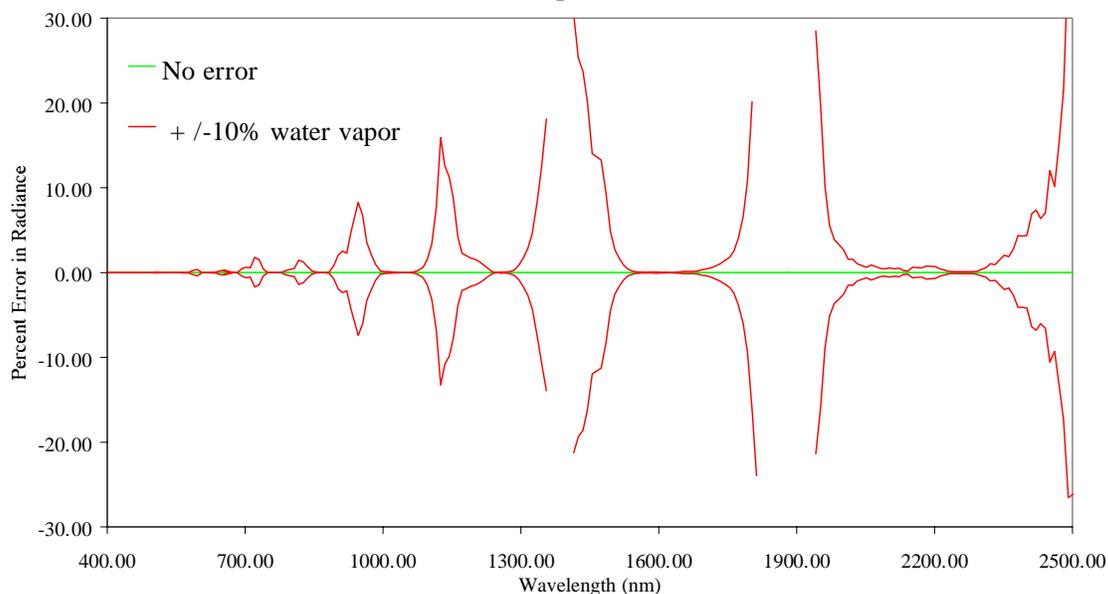


Figure 14. The error in MODTRAN predicted radiance as a function of the error in measured water vapor. Results are shown for no error and  $\pm 10$  percent error.

The sensitivity to knowledge of visibility is examined for errors of  $\pm 10$  percent and  $\pm 50$  percent for a 50-km visibility atmosphere. Visibility is the parameter in the MODTRAN radiative transfer code that most simply adjusts the effects of aerosols in the predicted radiance. Figure 15 shows the percent error in radiance as a function of error in visibility. With a baseline visibility of 50 km, even errors of 50 percent do not introduce large errors in the predicted radiance. This implies that for clear sky conditions, the predicted radiance is not strongly sensitive to the knowledge of visibility. There is an anomalous cross-over region in the visible portion of the spectrum due to the shape of the calibration target reflectance spectrum and the spectrally dependent effect of visibility on the predicted radiance.

There is significant difference in the sensitivity of the predicted radiance to the accuracy of the three in situ measurements investigated here. The predicted radiance is most sensitive to the knowledge of surface reflectance. Only portions of the spectrum near the atmospheric water vapor bands are strongly sensitive to the accuracy of the in situ measured water vapor. The predicted radiance is least sensitive to the accuracy of the visibility constraint parameter for these clear sky conditions. This sensitivity analysis provides a basis for allocation of effort when working to improve the accuracy of the in situ measurements needed for an in-flight calibration experiment.

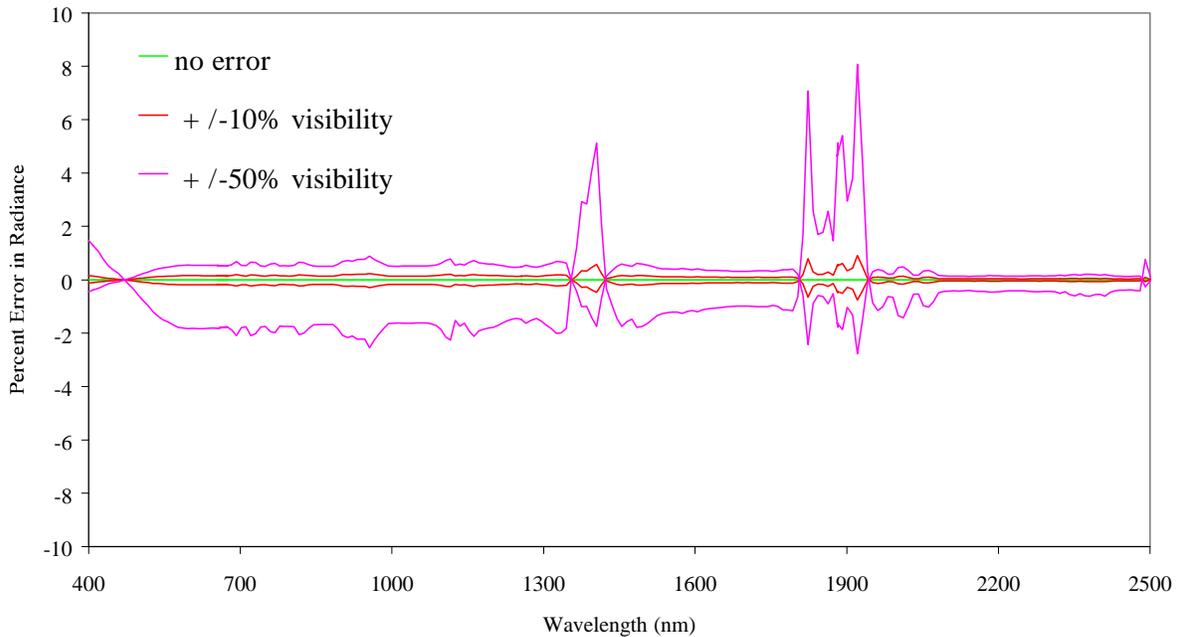


Figure 15. The error in MODTRAN predicted radiance as a function of error in measured visibility. Results are shown for no error as well as  $\pm 10$  percent and  $\pm 50$  percent error.

## 7.0 INTRAFIGHT STABILITY RESULTS

AVIRIS acquired data over the Rogers Dry Lake calibration target five times at approximately 12-minute intervals. These five consecutive images of the same target provide an opportunity to investigate the intraflight stability of AVIRIS. Figure 16 shows the calibrated AVIRIS radiance spectra for the five calibration target acquisitions. The radiance in each consecutive acquisition increases because the solar zenith angle was decreasing as the time approached local solar noon. To compensate for this zenith angle effect, MODTRAN spectra were calculated for the times of the five AVIRIS acquisitions of the calibration target. The MODTRAN-modeled change in radiance was then normalized out of the five AVIRIS data sets. Figure 17 shows the five calibration target spectra after compensation for the change in solar zenith angle. To assess the residual variability, the deviation from the mean was calculated for these spectra and is shown in Figure 18. This figure shows a baseline variation of just under one percent outside the strong water vapor absorption zones. This variation may be due to surface bidirectional reflectance effects, changing atmospheric effects, calibration target sampling effects, or changes in AVIRIS performance. In the spectral regions of the water vapor absorptions, clear effects are shown due to the change in water vapor during the five data acquisitions. These five data sets show that the combined stability of the illumination, surface, atmosphere, and AVIRIS was better than 1 percent with the exception of atmospheric water vapor regions of the spectrum.

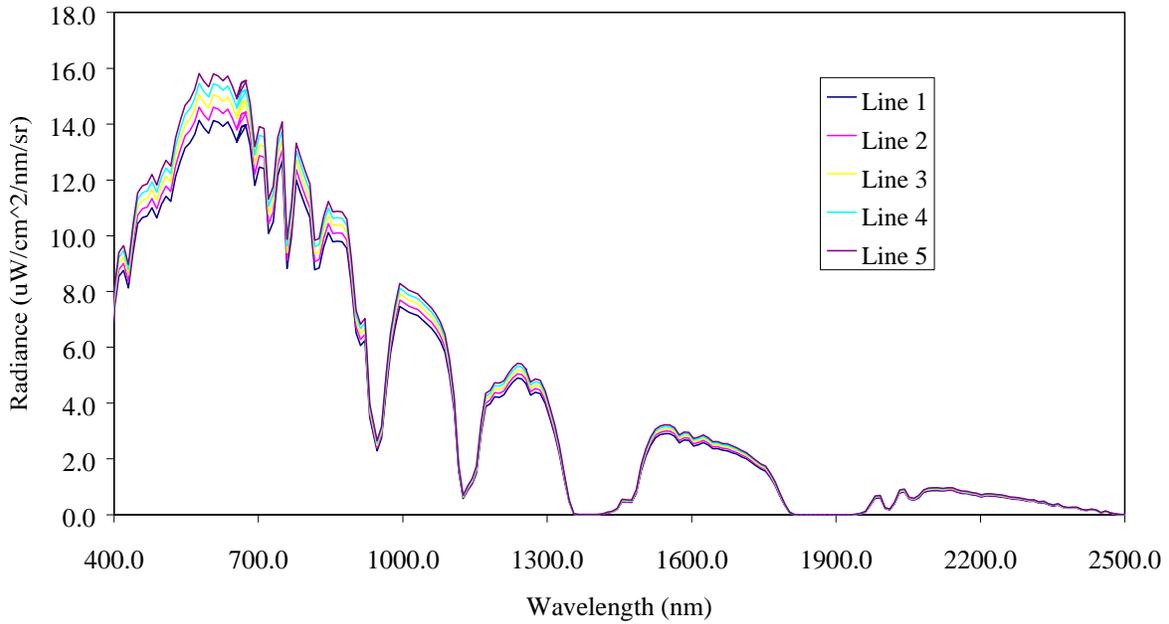


Figure 16. The radiance measured by AVIRIS for the Rogers Dry Lake calibration target is shown for the 5 consecutive overflights on 24 September 1999.

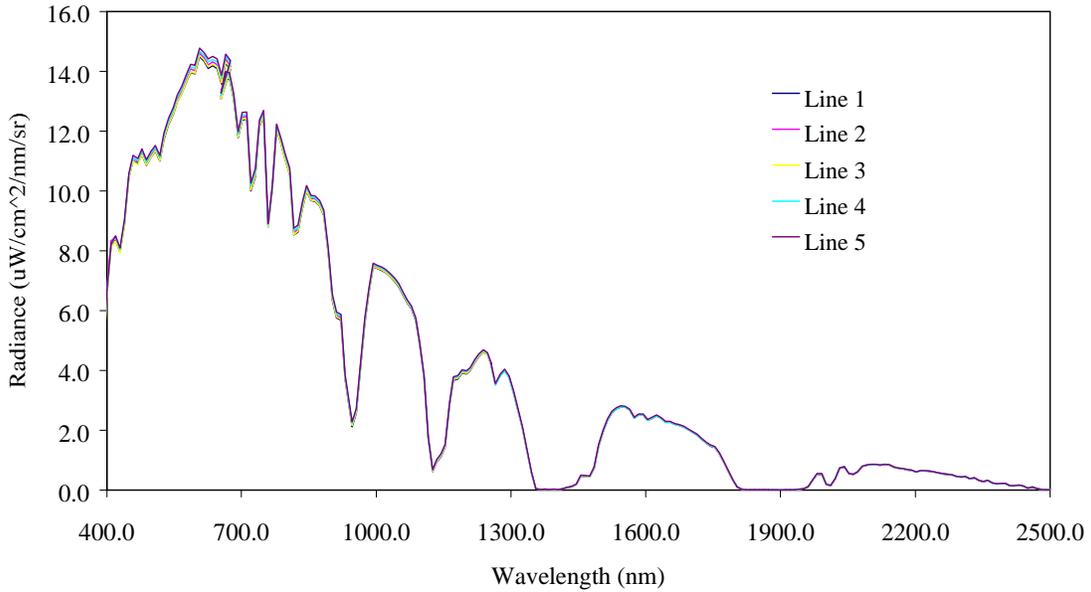


Figure 17. The AVIRIS radiance spectra after correction for zenith angle differences from the 5 consecutive overflights of the calibration target.

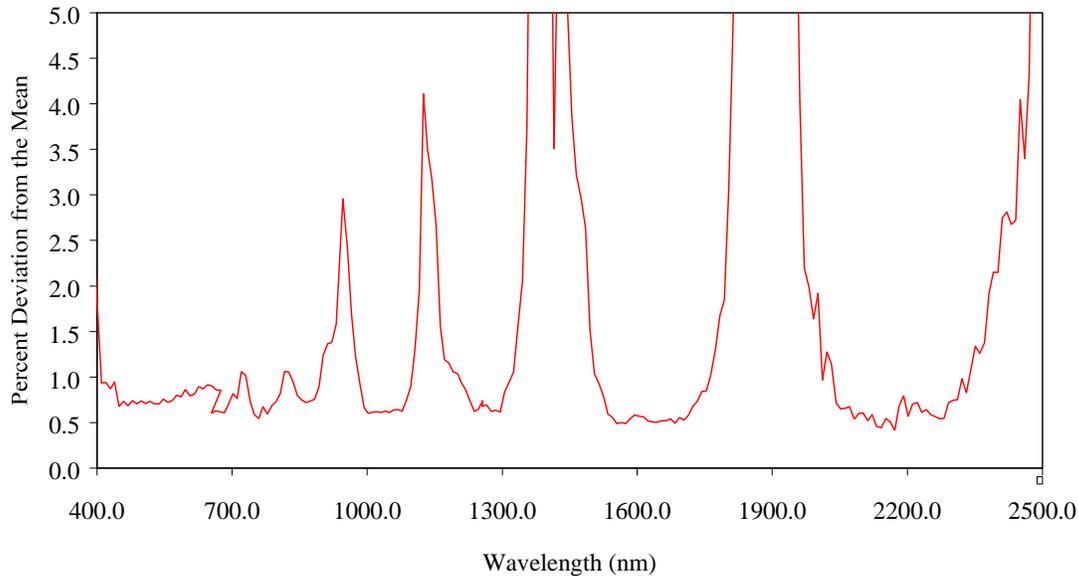


Figure 18. The percent deviation from the mean for the five zenith angle corrected overflights of the Rogers Dry Lake calibration target on the 24<sup>th</sup> of September 1999.

## 8.0 CONCLUSION

On the 24<sup>th</sup> of September 1999, an AVIRIS in-flight calibration experiment was performed at Rogers Dry Lake, California. The primary objective of this experiment was to validate the calibration of AVIRIS in the flight environment. In situ surface reflectance and atmospheric measurements were acquired at a designated calibration target and used to constrain the MODTRAN radiative transfer code to predict the radiance arriving at the AVIRIS instrument. In the same time frame as the surface measurements, airborne AVIRIS data were acquired over the calibration target. A comparison of the MODTRAN predicted radiance and the AVIRIS measured radiance spectra for the calibration target shows an average absolute agreement of better than 96 percent.

The radiometric precision of AVIRIS was assessed based on signals from the onboard calibrator. As expected based on engineering modifications, the NE $\delta$ L for 1999 was shown to be improved over 1998. The SNR for the AVIRIS reference radiance signal shows a peak of over 1000 at 600 nm and 500 at 2100 nm.

A sensitivity analysis was performed to examine the effect on the predicted radiance of the accuracy of the in situ measurements. A strong (nearly one-to-one) sensitivity was found for the accuracy of the surface reflectance measurement. The sensitivity to the accuracy of the knowledge of water vapor was strong in the spectral vicinity of the atmospheric water vapor absorptions. For the clear sky conditions of this calibration experiment, only a comparatively weak sensitivity between predicted radiance and the accuracy of the visibility constraint was found. The measurement of the surface reflectance is the most critical parameter of the in-flight calibration experiment.

AVIRIS acquired five consecutive data sets over the Rogers Dry Lake calibration target. The five sets of spectra for the calibration target were extracted and analyzed. The changes in radiance due to change solar zenith angle were compensated. The residual stability was assessed and presented as the deviation from the mean of the five spectra. A baseline variation of slightly less than 1 percent was found. Larger variations occurred near the atmospheric water vapor absorptions. The variation is attributed to a number of possible sources. These include uncompensated illumination effects, surface bidirectional reflectance properties, changes in the atmosphere, errors in the calibration target data extraction, and variability in AVIRIS instrument performance. In total, a less than one percent baseline variation was found over the one-hour period over which the five AVIRIS data sets were acquired.

A majority of the Earth science research and applications objectives pursued with AVIRIS required that the AVIRIS data be calibrated. All of these research and application efforts use AVIRIS data acquired in the flight environment. These in-flight calibration experiments provide a basis to assess and report the calibration of AVIRIS in the flight environment.

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